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## DIGITAL FOOTPRINTS AS A MEANS TO AID THE UNDERSTANDING, MONITORING AND MANAGEMENT OF OPEN AND CROWD BASED DESIGN PARADIGMS

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### ABSTRACT

Open Design and crowd-sourced development have recently formed a new paradigm in the engineering design and manufacture industries. Through collaboration and free sharing of information, open design has proven capable of developing complex products at a low cost, utilising an expert and motivated work force to bring products to market. However, as open design differs greatly from traditional engineering enterprise in several ways, there are challenges in its effective utilisation. This paper proposes an approach (termed *engineering project health monitoring*) to addressing two challenges; automatically generating a shared understanding of project-specific information, and providing the means to aid workflow management in the open design situation. As open design is often performed through distributed individual working, and is often subject to little management structure, aiding the generation of a shared understanding and control of activity scheduling and prioritisation are vital to ensuring a high-performing output.

**Keywords:** open design, crowdsourcing, engineering project health monitoring

### 1 INTRODUCTION

With the evolution of technology and in particular the internet over the past two decades, significant changes have occurred in the field of engineering manufacture and design. From the manual, co-located drawing offices of the mid-twentieth century, engineering is now a digital, multi-national, and multi-disciplinary affair potentially involving many thousands of engineers developing many hundreds of thousands of components (Florice and Miller 2001; Regli 2010; Watson 2012).

Outside of the walls of the more traditional and increasingly complex engineering enterprise, this technological advancement has led to the feasibility of a significant and very different model of the engineering development process, that of Open Design (OD), analogous to the Open Source Software (OSS) movement that has gained both traction and results over the last decade (Koch and Tumer 2009). This approach is characterised by its information management approach, that of free sharing of knowledge about a new design with the intention of its use for (and personal buy-in to) the collaborative development of a product or products (Raasch et al. 2009). This often occurs in an open market, with independent participants following calls for input through websites and repositories and working without monetary expectations, although commercial exploitation and profit has been explored and demonstrated (Howard et al. 2012).

As is to be expected considering its variance from the typical engineering approach, OD has specific characteristics and challenges that reflect the nature of the participants typically involved in such ventures and the artefacts that they develop (Raasch et al. 2009), stemming from the independent and fluid nature of OD. This paper presents an approach to addressing two of these challenges, which are also present in many larger scale, distributed teams; that of generating a shared understanding and

awareness between individuals and teams that is so important for high performance (Sarma and Van Der Hoek 2006), and that of managing, controlling, and optimising the highly fragmented groups of activities that are performed across the distributed process. The proposed approach involves the analysis of the project's *digital footprint*; that is, the digital files that are generated by participants throughout the design and manufacture processes. By gathering and analysing these *digital assets* (DAs), this work proposes that awareness, understanding, and management within OD and highly distributed engineering projects can be improved, with the potential for increased viability and process performance.

## 2 BENEFITS AND CHALLENGES OF OPEN SOURCE DESIGN

In the software world, the innovation model of Open Source Software (OSS) has become commonplace over recent years. Through sharing of source code over the internet and the open innovation paradigm highly significant software packages have been successfully developed, including the widely used operating system Linux, the mobile operating system Android, and both the Chrome and Firefox internet browsers. This vast success has come hand-in-hand with significant study within research (see von Krogh and von Hippel 2006).

Open Design (OD), in which tangible goods are developed through the open development model (Raasch et al. 2009), is a more recent branch from this approach that has seen some success in a number of projects. Research within the field is still in its infancy, with researchers performing exploratory thinking and case study analysis around such OD projects as RepRap (an open source 3D printer), Neuros OSD (home entertainment), and Oscar (a sustainable mobility concept). To date, the majority of this research has focused on the specific features of OD in comparison to both OSS and traditional engineering approaches (see Balka et al. 2009; Koch and Tumer 2009; Raasch et al. 2009; Howard et al. 2012), in particular the benefits and challenges to its performance. Though research into OD directly is currently limited, it shows potential benefits in:

- Ability to develop complex products, particularly with high modularity (Raasch et al. 2009)
- An expert develop/user base giving both the development and the testing (Howard et al. 2012)
- Potential for low-cost development (Howard et al. 2012)
- High market share through free-to-use business models, coupled with rapid distribution of the product through the market (Howard et al. 2012)
- High levels of capability and expertise through leverage of a large group of expert developers (Koch and Tumer 2009)
- Higher levels of optimization, specialization and variation within the product base through user development and branching (von Krogh and von Hippel 2006; Howard et al. 2012)
- Expectation of contribution amongst those involved within the development network (Raasch et al. 2009), and high participant motivation (von Krogh and von Hippel 2006)

Through benefits such as these, OD gives specific capability that is not always present within traditional engineering enterprise. Due to the large potential developer/expert/user-base there is scope for a highly parallel working process, with capability to deal with high simultaneous work loads. Through buy-in of many different participants with different specializations (and with access to different facilities) as is common within OD projects (Balka et al. 2009; Raasch et al. 2009), there is scope to reduce the needed in-house capability of those instigating the OD project. In tandem with these benefits however, the specific features of OD leads to challenges to overcome, such as:

- Difficulties in communication and sharing of information amongst a fragmented workforce (Koch and Tumer 2009; Howard et al. 2012)
- Unclear and inconsistent governance and management structure within and between OD projects (Raasch et al. 2009)
- Unclear routes to effective attribution of work (Osterloh and Rota 2007; Jakiela 2009)
- The difficulty in manufacture of tangible products amongst an inconsistently capable developer and consumer base (Balka et al. 2010; Howard et al. 2012)

Despite these challenges, the OD approach is growing in traction and capability. This paper continues by exploring the means to meet the challenge of poor information transfer and awareness in OD (and broadly within wider engineering design and manufacture); the solving of which may aid in increasing through-project shared understanding and workflow optimization, amongst other benefits.

### **3 ROOT CAUSE OF THE ISSUES**

In any engineering project there are a number of vital characteristics to success, which will vary depending on the project situation. The specific characteristics of importance within OD are yet to be the subject of detailed research, although some work has suggested the importance of modularity in design to give success to more complex projects (Raasch et al. 2009), and the importance of communication and systems for management (Vallance et al. 2001; Koch and Tumer 2009).

Due to the potentially haphazard and certainly inconsistent structure of OD projects (Balka et al. 2009) and lack of a consistent medium for communication, and high fragmentation of workforce, it is likely that there are issues hampering performance of typical OD projects in team structures, team cohesion, and within-project awareness. Without the direct systems controlling, managerial activity, and information flow that engineering requires, OD has to rely on efficient information behavior of its participants – particularly difficult when they are multi-disciplinary and highly distributed.

Consequently, without these systems, it is reasonable to assume that OD projects are highly likely to under-manage or even neglect key features of successful engineering enterprise, such as in managing information flow (McDonough 2000; Sosa et al. 2007), ensuring cross-project awareness of what is happening and why (Sarma and Van Der Hoek 2006), and effective management and leadership (Odeh and Battaineh 2002). This is particularly the case for projects where no hierarchical structure is present, there is little higher level management, and no contractual obligation is attached to work itself (Weber 2004). In these cases it is all but impossible to be aware of activity between participants and to control workflow effectively.

Our proposition is to reveal these features through monitoring and analysis of the DAs created in OD; analysed and used to aid information flow and awareness between participants, and to monitor and elucidate activity and workflow. This is a complex task even in highly controlled engineering situations, and more so when a fragmented and uninformed network of participants is employed. This paper continues by describing and exploring this approach as applied to support OD throughout design and manufacture.

### **4 THE EPHM APPROACH TO INFORMATION GENERATION**

Ubiquitous within all modern engineering projects, and of necessity within OD, are the use of digital media throughout the design and manufacture processes. Through the files that all participants create during their activities - including reports, emails, presentations, CAD files, simulation files, drawings, analyses, etc. – a digital footprint of the project is created; on an individual, project, or company level, and throughout the project hierarchy. By utilising these Digital Assets (DAs) as a representative data source within a project, it is possible reveal an understanding of what is happening within a project algorithmically, and in some cases entirely automatically.

This approach (termed Engineering Project Health Monitoring – *ePHM*) takes low-level data and uses it to give high-level understanding, largely analogous to the process of integrated vehicle health monitoring as employed within the fields of machine design and maintenance (see Jennions 2011). By using DAs as a steady source of data and sensing certain characteristics of their creation, modification, and content, it is possible to infer high level project understanding (Snider et al. 2014; Snider et al. 2015). For example, textual content of emails can be used to infer project phase transitions, working focus and shifts in focus, and scope creep and complexity (Jones et al. 2015); and CAD file creating and modification dates can be used to infer product dependency, progression rates and activity levels, and predict completion dates (Gopsill et al. 2015 (in press)).

While *ePHM* is primarily developed for the purposes of information and aiding project managers within larger companies, there is also scope for its use as a tool to increase awareness within OD. By providing analyses of the DAs created during OD processes by all participants as they are developed and distributed, an *ePHM* system affords the opportunity to provide a number of snapshots of the project situation, progression, and collaborators throughout the process automatically and without managerial collation, to be used both within the design and manufacture processes.

In practice, *ePHM* attempts to provide information according to a detailed and comprehensive list of project features, each known to be important for overall project performance (Snider et al. 2015). While the comparability of this list and relative importance of its features to OD is not known, it is reasonable to assume a logical subset of important features exists. Some features relevant to

increasing awareness and aiding workflow are listed in Table 1. Through the availability of more detailed information targeted towards features of OD projects such as these, *ePHM* analyses may provide the means to improve both the design and manufacture processes through a number of ways. Two such alternatives are explored within the following section, both of which use real data from engineering projects.

#### 4.1 Features of Information Flow and Awareness

There are a number of features of good projects that relate to their information flow and awareness of participants about wider project knowledge. As these areas are a potential weakness within OD, they form the targets for analysis by *ePHM*. Examples of such features that are likely of specific importance to OD are given in Table 1, and are as developed and defined in Snider *et al.* (2015).

Table 1: Features of projects that have potentially poor understanding in OD

	<b>Feature</b>	<b>Definition</b>
Person	<b>Awareness Level</b>	Awareness of an individual of activity external to their personal work
	<b>Experience</b>	The amount, type, and breakdown of experience of an individual
	<b>Roles</b>	The roles of an individual within the wider project
	<b>Structure</b>	The hierarchy and authority between contributing participants
	<b>Workload</b>	The amount of completed and pending work of an individual
Product	<b>Criticality</b>	The importance of the individual output of activity in terms of consequence of failure to meet requirements
	<b>Dependency</b>	The inter-relationship between components in the design output
	<b>Complexity</b>	The sequence and number of functions that the product must perform
	<b>Progress Level</b>	The progress of the design output as a proportion of functional completion
	<b>Technical Difficulty</b>	The intellectual difficulty of forming the design
Process	<b>Criticality</b>	The importance of the specific process in terms of consequence of failure of completion
	<b>Dependency</b>	The inter-relationship between activities in the design process
	<b>Progress Level</b>	The progress of tasks within the project as a proportion of process completion
	<b>Sequence complexity</b>	The sequence, number of steps, and iterations required to perform the process
	<b>Technical Difficulty</b>	The intellectual effort of following the process
Info	<b>Information Diffusion</b>	The distribution of information through the organisation
	<b>Information Structure</b>	The pathways and ease of information access through the organisation
Activity	<b>Activity Focus</b>	The elements of the project or output on which work is being performed
	<b>Activity Level</b>	The level of activity being performed by an individual or group

Each of the features within Table 1 aids project performance in typical engineering enterprise, and is likely to be sub-optimal in OD due to the specific characteristics of OD projects. By providing information according to these features, particularly if provided automatically, there is potential to increase performance of OD projects in two way; through revealing information that aids work breakdown, personal, and team management of activities, and through allowing streamlining of workflow through quality of output, and through streamlining of design and manufacture processes. The following section outlines potential benefits of additional understanding of some of these features and demonstrates the potential value of the *ePHM* approach in OD through the use of two real-data examples; one looking at increasing understanding of the work being performed by others, and the other looking at streamlining and understanding of work flow for better planning of future activity.

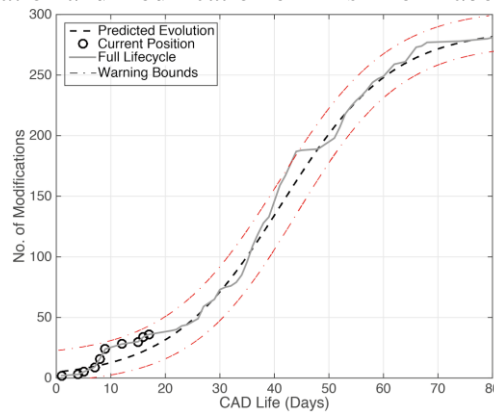
## 5 INCREASING AWARENESS IN OD THROUGH AUTOMATIC TECHNIQUES

This section demonstrates the way in which automatic techniques may aid design and manufacture in OD. This is enabled by the transition of all DAs related to an OD project through a single centralized system, likely through the internet, that plays the sole role of analyzing and presenting project-specific information. Such systems have been proposed and explored within OD by others (Vallance et al. 2001). Through the information that is presented, participants are able to self-manage and optimise their own processes. Both examples given here are taken from real data, and the techniques by which they are performed are detailed in other work. Here they are used to illustrate the ePHM approach.

### 5.1 Interpretation through creation and modification of digital objects

When a DA is created or modified, the dates of this change are recorded in its meta-data. By capturing and analyzing these creations and changes, and relating them to the creation and changes in other DAs, information about the project itself can be inferred. Figure 1 demonstrates this concept for CAD files. For this analysis, CAD files were extracted from a formula student project at the University of Bath. The creation and modification dates of all CAD files were captured automatically through the shared drives of the engineers. More detail can be found in (Gopsill et al. 2014; Snider et al. 2014).

The creation and modification of a CAD file, or many DAs, when the DA is finalized, follow a sigmoid function; little activity initially, followed by a high rate of activity, followed by a slowing and plateau. By modelling the creation of a DA as a sigmoid function at any given point in time according to a controllable margin of error, it is possible to predict the likely point in time at which the modification will plateau – ie. When the CAD component or assembly will be finalized. This technique is reported in detail in (Gopsill et al. 2015 (in press)) and allows accurate prediction of end-point from about 40% of the development time. In addition, as summarized in Table 2, the characteristic patterns in creation and modification of DAs inform about several other project features.



**Figure 1: CAD file creation and modification through sigmoid curves**

### 5.2 Interpretation through sequence analysis of activities

By looking at the reports and documents created through a design and manufacture process, as well as the types of DA produced (ie. CAD file, FEA analysis, technical drawing, final report), it is possible to infer the activities that are being completed. These activities can then be studied in terms of their sequence, complexity, time-to-completion, likely next activities, etc. Figure 2 shows a number of these sequences as automatically extracted from individual repair projects of damage to airplanes, as gathered from an international aerospace company. Each project was packaged as a report with a number of documents within, with the activities performed and their sequence extracted through document types and dates of occurrence. More detail of the analysis found at (Shi et al. 2014).

In Figure 2, each individual step indicates an activity as extracted from the dataset. The sequence of these activities can be analyzed to predict future activities, time-to-completion, and project complexity from an early stage. Detail on these analyses can be found in (Shi et al. 2014). From these analyses it is possible to interpret information about a number of project features within OD, as described in Table 2.

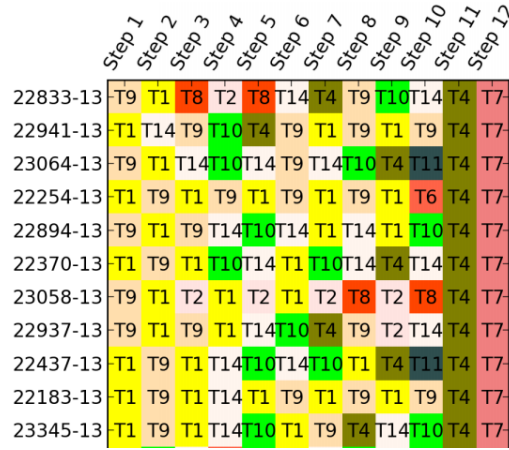


Figure 2: Activity sequences from individual repair projects

### 5.3 ePHM and information that aids Open Design

The analyses briefly presented in the previous sections can automatically infer project-level information from individual DAs. As they are passive in nature and require only that the DAs pass through a central repository they are highly suitable to the OD paradigm, where working DAs are distributed directly to project participants through the internet. By placing an ePHM system within the DA distribution network there is potential for information to be provided according to these analyses, as described in Table 2.

Table 2: Interpreting project features from analyses

Feature	Analysis Type	
	Creation / Modification	Activity Sequence
<b>Workload</b>	Activity progress through gradient of sigmoid function for a given DA.	Future workload through upcoming activity sequence predicted and time-to-completion.
<b>Product Dependency</b>	The time-lag between sigmoid functions for different components	--
<b>Product Complexity</b>	The number of components simultaneously being developed and dependent upon one another	--
<b>Progress Level</b>	The cumulative sigmoid gradients for final assembly files	The current activity in comparison to typical "complete" activity sequences
<b>Process Dependency</b>	--	The typical preceding activities for any given activity
<b>Sequence Complexity</b>	--	The typical length of predicted activity sequences and typical sequence iterations
<b>Activity Focus</b>	The component or system upon which work is being performed	The activities that are being performed across the participant network
<b>Activity Level</b>	The cumulative sigmoid gradients for all files being developed	The rate at which the sequence of activities is progressing

## 6 AIDING OPEN DESIGN DEVELOPMENT AND MANUFACTURE

Table 2 has described a number of ways in which an ePHM approach could provide information that aids OD, particularly in terms of generating a shared understanding and aiding workflow optimisation and management. This is a far from exhaustive list focusing as it does on only two types of analysis; in reality more could be employed.

Within the development stages of OD, the analyses in Table 2 focus on increasing understanding of the work being performed by other individuals; effectively revealing activity throughout the project structure. Knowledge of the type of work being performed by others, their workload and rate of activity, and the subject of their work, allow a participant to optimise their own activity and choose

what they do effectively; for example, by ensuring that their work is completed when it will be needed as input by others, choosing activities to perform on systems that are appropriate to the wider workflow of the project, and knowledge of the work breakdown between participants – highlighting for example where certain systems or activities have been neglected. Due to the lack of centralised management and systems to monitor and control work in OD environments, and evidenced by the reliance on such systems in traditional engineering enterprise, such information may prove invaluable in increasing the efficiency and effectiveness of the OD process.

Manufacture is a particular challenge in OD due to a lack of availability of facilities for participants. Beyond aiding the general management of scheduling and organisation of activities, the analyses within Table 2 have potential to aid OD manufacture through optimisation of workflow, streamlining processes with the knowledge that manufacture capability is limited. For example, prioritisation and scheduling of activities to minimise the number of manufacture episodes, grouping of work on similar or related components so that all can be manufactured at once, predicting time-to-complete to organise manufacture in advance, or postponing manufacture until all work on related systems is ready, hence reducing need to re-make.

## **7 SUPPORTING CROWDSOURCED DESIGN AND MANUFACTURE**

In recent years, the open source paradigm has shown success within the software field and some promise within hardware. However, due to the inherent differences between OD environments and more traditional engineering enterprise, there are a number of challenges to effective OD execution.

Key among these are the distributed and individually working nature of participants in OD projects. Through the internet it has become feasible for very disparate groups, both geographically and experientially, to work together to common goals, but due to their separation and the difference in types of activities that they perform and in which they are expert, a fundamental lack of awareness of the wider project threatens to appear. Coupled with this there is often a lack of direct management or inconsistent structure within OD, with the potential to lead to poor workflow and structuring of the project as a whole.

This work has proposed an approach to revealing project specific information within OD that may aid these issues. The *ePHM* approach is an automatic process that analyses low-level engineering data, such as CAD files, emails, and reports, and uses it to infer higher level project information. OD projects are often missing the various systems that aid in this process in traditional engineering, and lack the management structure that forms teams, delegates and monitors work, disseminates information, and controls and schedules the workflow sequence. As a result, the targeted and automatic approach of *ePHM* is particularly suited to OD working; passing all digital assets through a single analytical system provides the potential to generate such useful information without the presence of a manager or active-and-direct interpretation by a participant.

Within any project, there are a wealth of features that are important to success. In OD, the specific subset that are potentially inferior to traditional engineering can be hypothesized as targets for the *ePHM* approach. The feasibility of assessing and informing about these features has been presented in this work through two detailed forms of automatic analysis, each performed on real data from engineering projects. Through these analyses, a number of indicators of project information are proposed, tailored to specific challenges of OD. In reality many more analysis techniques are viable within the *ePHM* approach, with a complete system generating information from all digital interactions made by the project participants.

Throughout OD, the automatic provision of project-specific information through *ePHM* has potential to greatly increase overall performance, by providing access to information resources that are neglected in OD, but have proven vital in traditional engineering enterprise.

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